

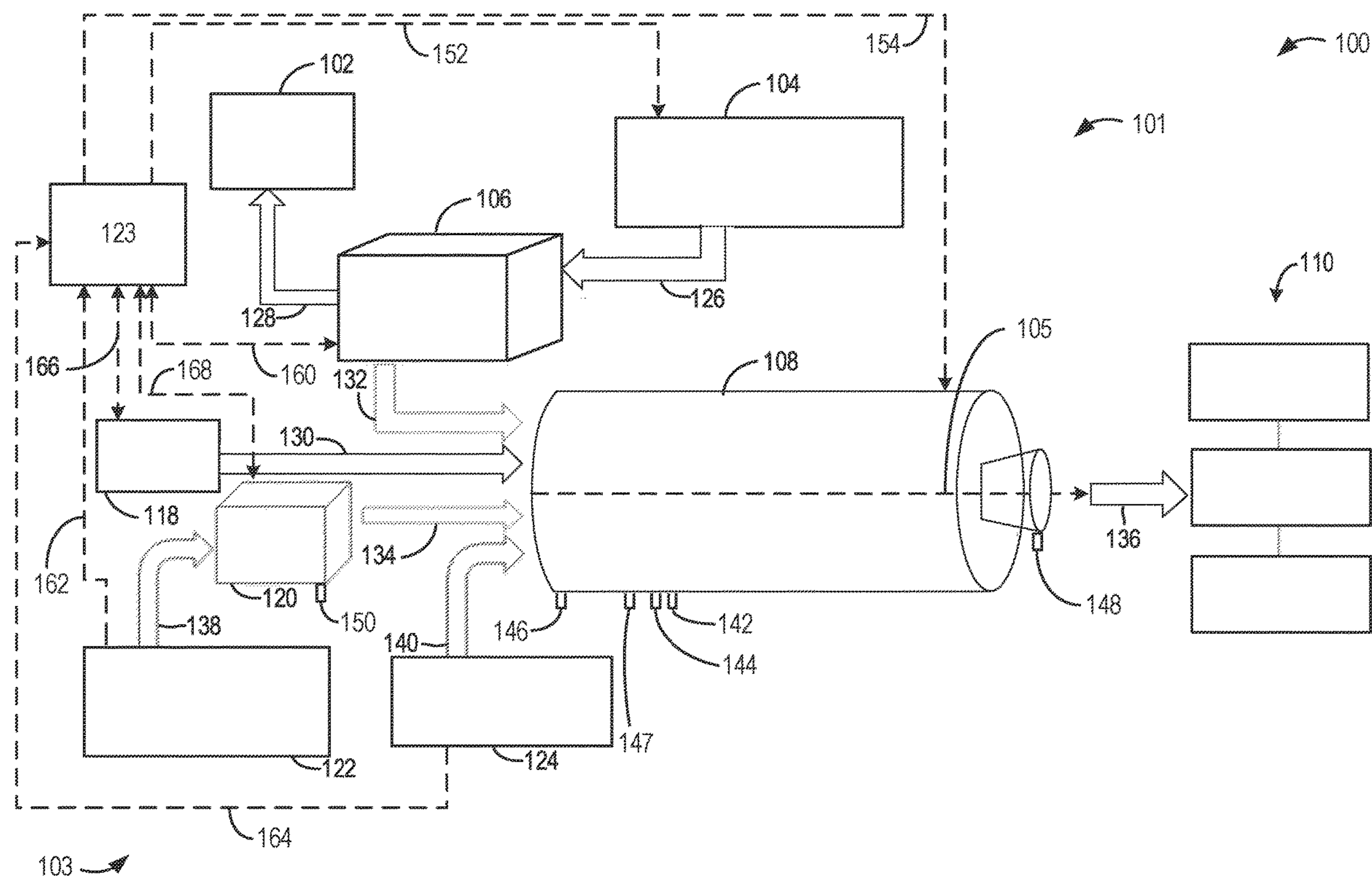
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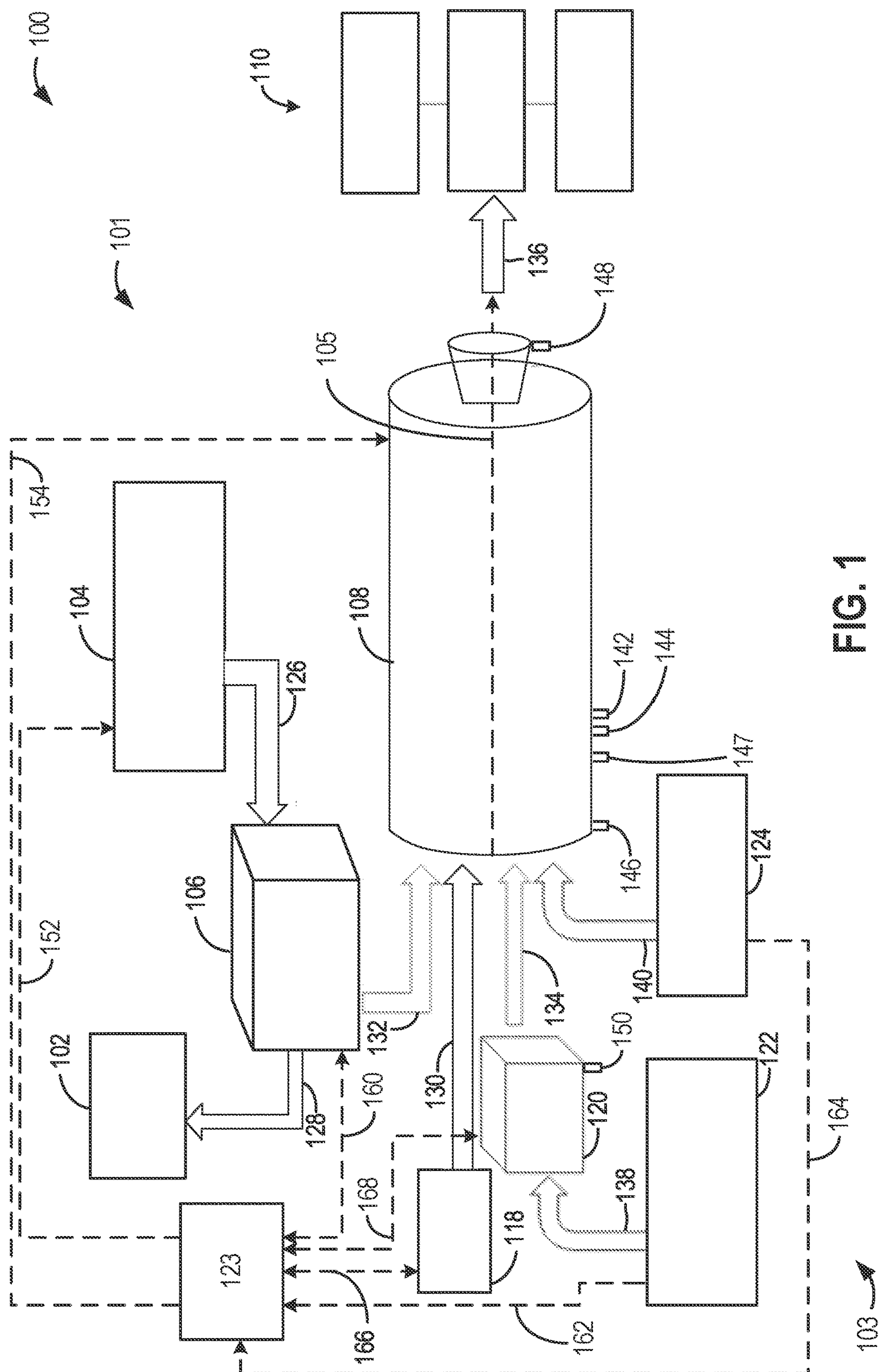
(19) **United States**(12) **Patent Application Publication**
Whitehill et al.(10) **Pub. No.: US 2023/0097058 A1**(43) **Pub. Date: Mar. 30, 2023**(54) **THERMOMECHANOCHEMICAL WASTE
TREATMENT****Publication Classification**(51) **Int. Cl.****C02F 11/18** (2006.01)**C02F 11/00** (2006.01)**C02F 11/13** (2006.01)**B09B 3/00** (2006.01)(52) **U.S. Cl.**CPC **C02F 11/18** (2013.01); **C02F 11/004**
(2013.01); **C02F 11/13** (2019.01); **B09B**
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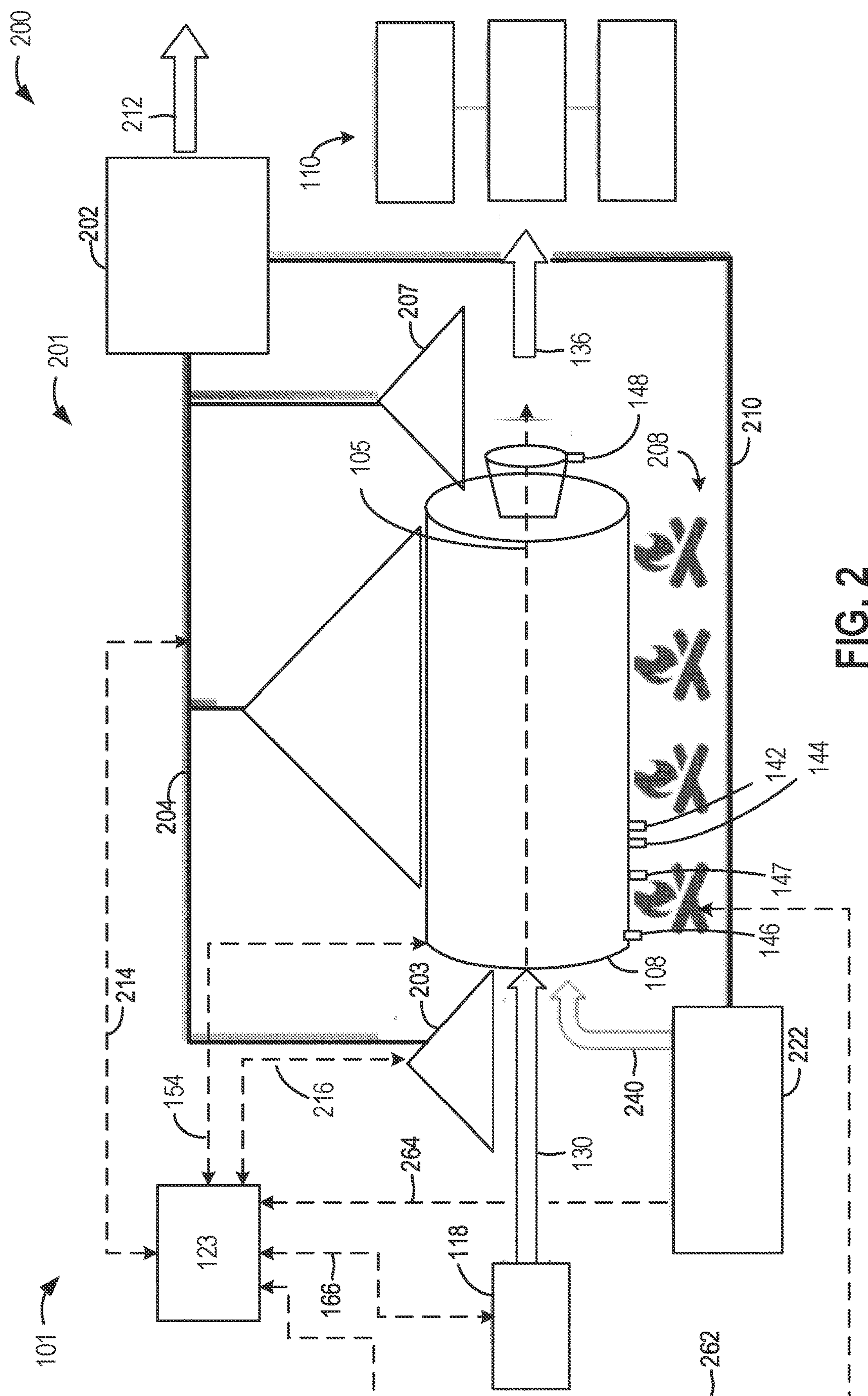
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ABSTRACT

Methods and systems are provided for processing PFAS-contaminated waste via thermomechanochemical (TMC) processing. In one example, a system may include a TMC processing chamber including a milling system and coupled to a heating system, the heating system configured to cooperate with the milling system to process the waste material. A plurality of containers including the waste material in one or more of a liquid-solid state, a semi-wet or slurry solid state, and a dry solid state are coupled to the TMC chamber.







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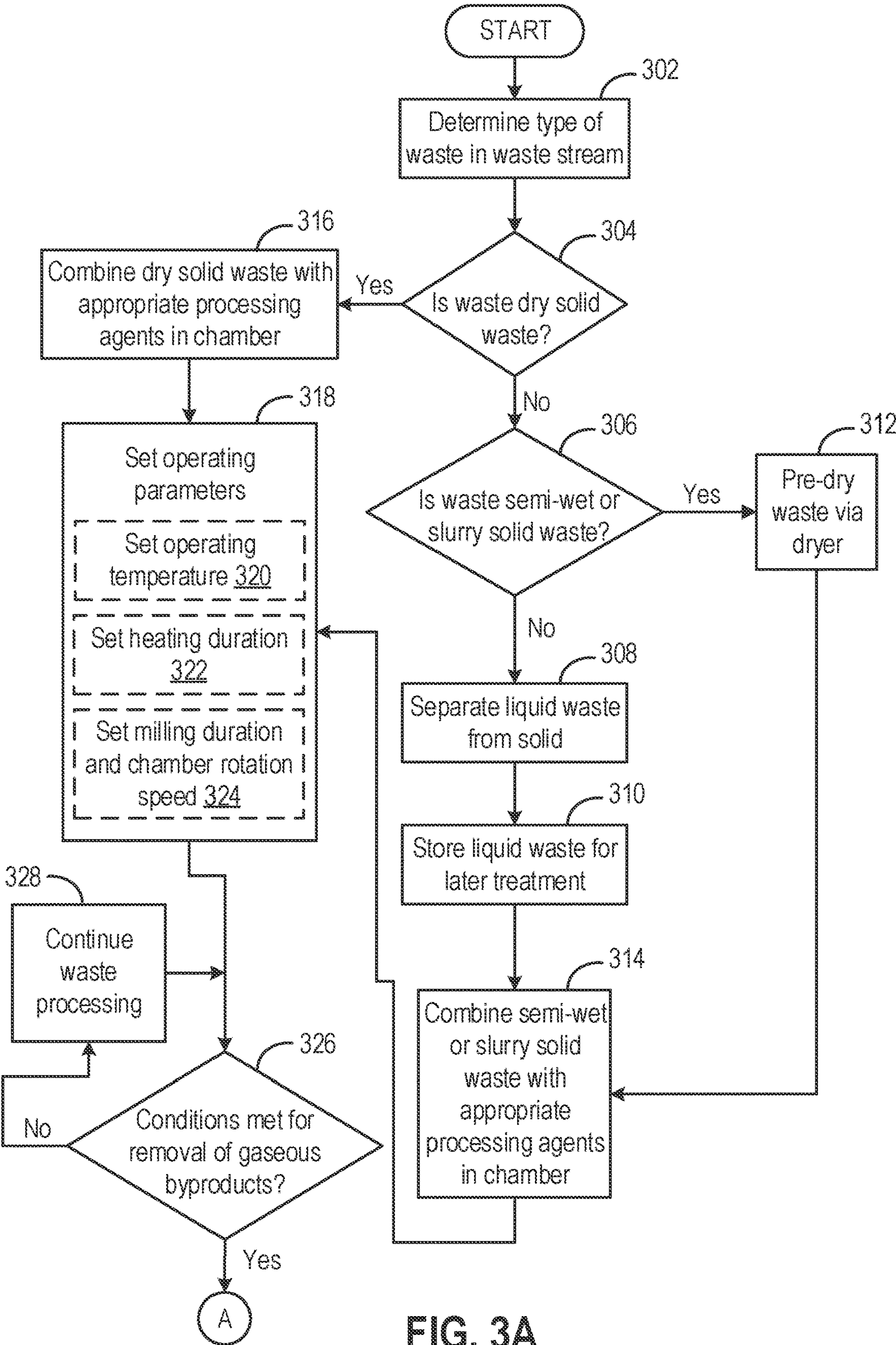


FIG. 3A

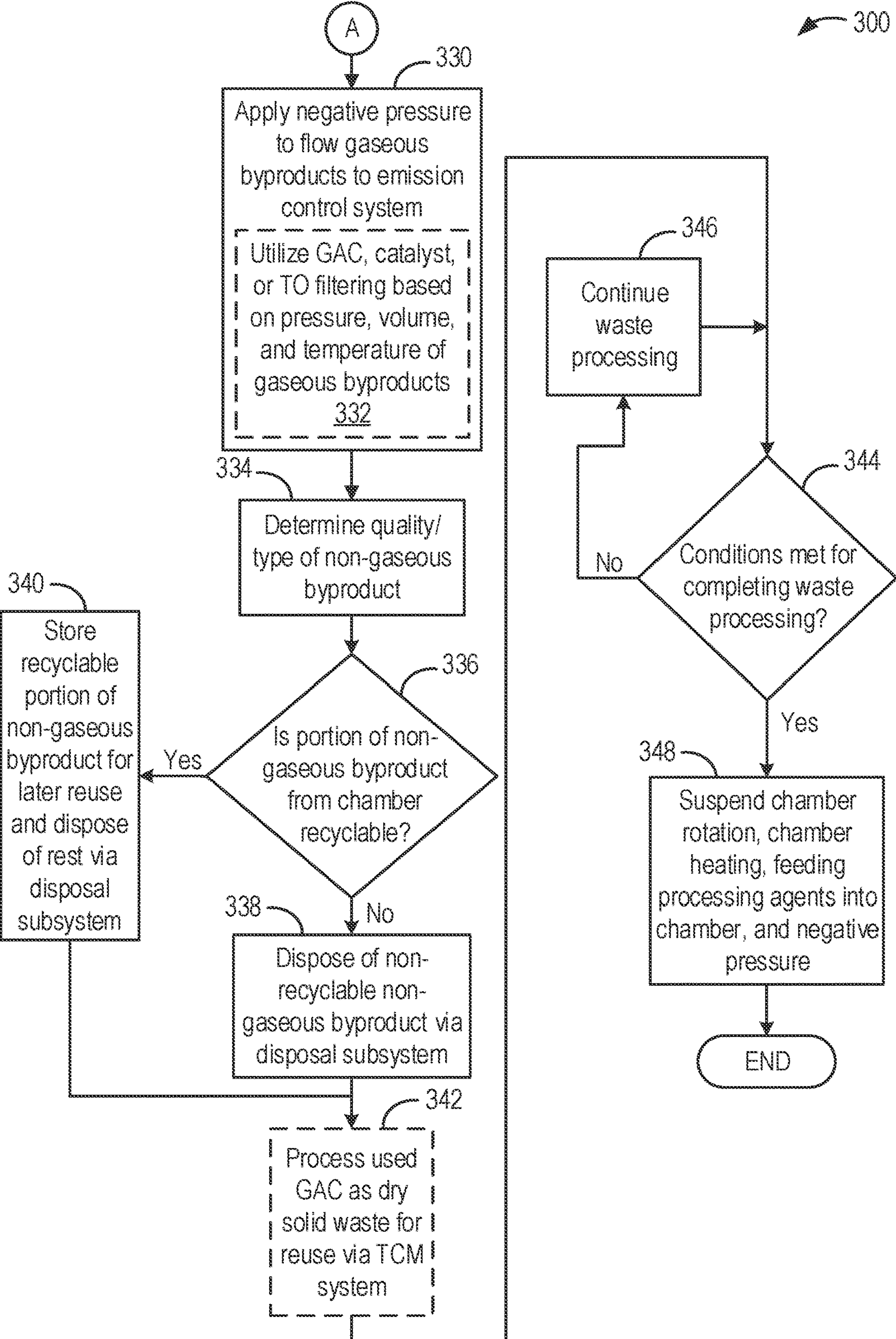


FIG. 3B

THERMOMECHANOCHEMICAL WASTE TREATMENT

ACKNOWLEDGMENT OF GOVERNMENT SUPPORT

[0001] This invention was made with government support from the United States Environmental Protection Agency through its Office of Research and Development. The government has certain rights in the invention.

CROSS REFERENCE TO RELATED APPLICATIONS

[0002] None

FIELD

[0003] The present description relates generally to systems and methods for a thermomechanochemical (TMC) waste treatment system for treatment of waste including pollutants such as Per- and Polyfluorinated Substances (PFAS).

BACKGROUND AND SUMMARY

[0004] Per- and polyfluoroalkyl substances (HAS) are a group of synthetic chemicals that includes perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), and GenX, among others. HAS have been manufactured and used in a variety of industries around the globe, including in the United States since the 1940s. Many chemicals in this group, including perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), are of concern and are desired to be sustainably removed from waste material.

[0005] Additionally, while there are laws regulating manufacturing and importing of products containing PFAS (including the Safe Water Drinking Act, the Toxic Substances Control Act, the Comprehensive Environmental Response, Compensation, and Liability Act, and the Clean Air Act), PFAS already present in the environment is of concern. For example, PFAS moves through soils and contaminates drinking water sources, and builds up (bioaccumulates) in fish and wildlife. For example, PFAS have been found in rivers and lakes and in many types of animals on land and in the water. Additionally, PFAS may be found in landfills, wastewater lagoons, wastewater treatment facilities, and biosolid application areas. For example, PFAS may be contained in landfill leachate, and the landfill leachate may serve the main pathway for PFAS to exit municipal solid waste landfills. As HAS poses several health risks to public health, methods for processing waste containing PFAS are desirable.

[0006] Prior methods for removing PFAS from various media may include, for example, in situ thermal treatment of PFAS in soils at low temperatures ($< \approx 300^{\circ} \text{C.}$) or at higher temperatures through a variety of mechanisms. High temperature thermal treatment may not be desirable for certain waste feedstocks (e.g., the beneficial use potential for land application of biosolids may be reduced by high temperature thermal treatment). Additionally, low temperature embodiments of thermal treatment are not time efficient (requiring days), and is not efficacious. It is also known that mechanochemical treatment, such as ball milling with added processing reagents, can destroy pollutants, including PFAS (recent demonstration) in dry waste. However, the above described methods may not be universally applicable and/or

customizable to a plurality of waste media, including solid-liquid waste, semi-wet or slurry solid waste, and dry solid waste.

[0007] In one example, the issues described above may be addressed by a thermomechanochemical (TMC) chamber including a milling system, a heating system coupled to the TMC chamber, the heating system configured to co-operate with the milling system to process the waste material, and a plurality of containers coupled to the TMC chamber at a first end, the plurality of containers including the waste material in one or more of a liquid-solid state, a semi-wet or slurry solid state, and a dry solid state. In this way, PFAS may be removed from a plurality of waste media in a waste feedstock, allowing for systematic and customizable removal of PFAS for more efficient and efficacious waste processing. Additionally, other pollutants may be removed as part of the same process, creating added benefit.

[0008] It should be understood that the summary above is provided to introduce in simplified form a selection of concepts that are further described in the detailed description. It is not meant to identify key or essential features of the claimed subject matter, the scope of which is defined uniquely by the claims that follow the detailed description. Furthermore, the claimed subject matter is not limited to implementations that solve any disadvantages noted above or in any part of this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 shows a first schematic diagram of a thermomechanochemical (TMC) waste treatment system, including subsystems for various forms of waste.

[0010] FIG. 2 shows a second schematic diagram of a TMC waste treatment system, including subsystems for removal of byproduct after treatment.

[0011] FIGS. 3A, 3B show a flow chart of a method for operating a TMC waste treatment system, such as the TMC waste management system of FIGS. 1, 2.

DETAILED DESCRIPTION

[0012] The following description relates to systems and methods for thermomechanochemical (TMC) waste treatment for treatment of PFAS (and other pollutant)-affected waste feedstocks. In an exemplary embodiment, such as a TMC waste treatment systems of FIG. 1 and/or FIG. 2, TMC waste treatment may reduce excess levels of PFAS in PFAS-contaminated waste in order to achieve compliance with federal, state, or local regulations. The TMC waste treatment system may remove PFAS from a variety of different types of waste feedstocks, including dry solid waste, semi-wet or slurry solid waste, and liquid-solid waste, customizing process parameters during processing for each type of waste. A method for operating the TMC waste treatment system is provided in FIG. 3.

[0013] PFAS-contaminated waste feedstocks may be processed via a variety of methods, depending on the incoming waste feedstock. In one example, PFAS-contaminated waste, such as in a solid or semi-solid matrix, may be broken down via a mechanochemical degradation (MCD) process, such as via a deaggregator. Examples of deaggregator include free moving devices such as milling balls or stationary devices such as blocks, blades, etc. During ball milling, deaggregators (such as the milling balls) are included in a waste processing chamber (also referred to

herein as the TMC chamber), e.g. a cylindrical chamber, whereby the chamber is rotated along a central axis in order to provide milling of the PFAS-contaminated waste with the deaggregators. For types of waste on a thermal end of a processing spectrum, the TMC chamber may operate without deaggregators, and may use some other method to mechanically process (mix/grind) the material. For example, biosolids processing mechanical action may be designed to break open cells to facilitate vapor removal via another mechanical processing method, such as via milling blades included within the TMC chamber. Collisions of the PFAS-contaminated material with the deaggregators increases the surface area of exposure of PFAS contained within the material, may further break down PFAS, and may destroy a non-volatile fraction of PFAS contained within the PFAS-contaminated material. Furthermore, reagents, including, but not limited to, silica (SiO_2), potassium hydroxide (KOH), calcium oxide (CaO), and/or calcium hydroxide ($\text{Ca}(\text{OH})_2$) may be added to the TMC chamber in order to further react with PFAS contained therein. These reagents help produce highly reactive conditions for reaction with fluorine atoms in PFAS. The crystalline structures of the reagents are crushed and sheared by high energy impacts from the deaggregators (such as stainless-steel milling balls) in the rotating TMC chamber. Such collisions may produce radicals, electrons, heat, and even plasma that react with PFAS to produce inorganic fluoride compounds and graphite.

[0014] As an example, high energy milling of PFAS-contaminated waste with stainless steel balls and common sand (SiO_2) as a co-milling reagent can cause cleavage of the Si—O bonds in the sand particles, forming free radicals. These free radicals liberate fluorine from the PFAS, breaking down the PFAS and producing Si—F. Thus, high energy ball milling of dried PFAS-contaminated materials with common sand can destroy the PFAS, and convert the fluorine to harmless inorganic fluorine (surface Si—F bonds).

[0015] In order for ball milling with or without reagents to be effective, the PFAS-contaminated waste included in the milling process is desired to be in dry waste form. For PFAS-contaminated waste such as biosolids that form semi-liquid, slurry, or wet solid (SSS) waste, heating may be applied to the waste in order to remove the PFAS. During heating, the PFAS may volatilize off of the biosolid, and the volatilized PFAS, as part of a gaseous byproduct, may be further processed via an emission control system. For example, thermal treatment of PFAS in soils can be accomplished in situ or ex situ at low temperatures ($< \approx 300^\circ \text{C}$.) or at higher temperatures through a variety of mechanisms. High temperature thermal treatment is not desirable for certain waste feedstocks (e.g., beneficial use potential for land application of biosolids is ruined by high temperature thermal treatment). Low temperature embodiments of thermal treatment are not time efficient (requiring days) and may not be efficacious. The combination of optimal mechanochemical action (using deaggregators) and optimal thermal profile (with or without reagents) may produce the most efficient process throughput, removal/destruction efficacy, and potential for material beneficial reuse.

[0016] In the embodiments described herein, both the MCD and thermal treatment is combined into a thermo-mechanochemical (TMC) waste treatment system for treating, in a flexible and customizable manner, a variety of waste feedstocks, such as dry solid and SSS waste feedstocks. The

TMC waste treatment system may include a feeding system for waste material, including a plurality of subsystems configured to reduce moisture in the waste material prior to entering a TMC chamber, a plurality of sensors to estimate input pollutant levels and processing conditions, the TMC chamber including a plurality of deaggregators, a heating system configured to impart thermal energy to the TMC chamber, a processing reagent subsystem configured to deliver co-milling reagents to the TMC chamber, and a disposal system configured to remove gaseous and non-gaseous byproducts remaining after treatment of the waste material at the TMC chamber.

[0017] In such embodiments described herein, waste may come in a variety of available waste feedstocks, with each waste feedstock variety being pre-processed separately before being sent to main chamber for TMC treatment. For example, the pre-processing system may include several subsystems, including a first subsystem for liquid/solid separation to partition liquid from SSS waste. A second subsystem for storage (for later treatment) or direct processing of liquid streams as part of the process may be included. For SSS waste, a third subsystem dryer may be included for drying semi-wet or slurry solid waste prior to TMC treatment. For dry waste, a fourth subsystem bypass may be included to allow direct operation on dry waste that does not use liquid separation or drying. A fifth subsystem for adding processing reagent may be included, the fifth subsystem allowing storage and addition of specialized materials (e.g. reagents) to the SSS or dry waste feedstocks that will aid in the removal or destruction of PFAS during TMC treatment.

[0018] Following pre-processing via the aforementioned variety of pre-processing subsystems, the one or more waste feedstocks may be added, along with the reagents, to a TMC treatment subsystem. The TMC treatment subsystem may include removing and/or destroying PFAS and/or other pollutants from the SSS or dry waste feedstock via a heating system and via milling of waste material with deaggregators and added co-milling reagents within the TMC chamber. The subsystem produces one or more of the following effects: final drying, mixing and deagglomeration to expose surface area, thermal evolution (cleaning) of pollutants, and/or mechanochemical destruction of pollutants, with or without processing reagents.

[0019] Following treatment within the TMC subsystem, gaseous byproducts generated during the TMC processing which may contain PFAS and other pollutants may be treated via an emission control subsystem. The emission control subsystem may use a low pressure suction to capture the gaseous byproducts and control or destroy volatilized PFAS that may be released by utilizing one or more air pollutant emission control devices (e.g., a thermal oxidizer (TO), wet scrubber, cyclone, and/or sorbent media to capture pollutant, such as granular activated carbon (GAC)), with the optional processing feature of destruction of the spent filter (e.g., GAC) in the TMC system.

[0020] In this way, by sorting waste into different waste feedstocks (including liquid-solid waste, dry solid waste, and semi-wet or slurry solid waste), applying pre-processing to each of the waste feedstocks, treating the pre-processed waste feedstocks via TMC treatment, a plurality of different waste feedstocks may be processed to remove PFAS therein. The technical effect of combining thermal treatment and mechano-chemical treatment to the pre-processed waste feedstocks is that a synergistic approach offered by TMC

provides cost effective treatment of the waste feedstocks. The mechanical aspects assist in the thermal processing, and the thermal processing augments the mechanochemical kinetics with select catalytic reagents and co-milling reagents. Waste material, e.g., biosolids formed from sewage and contaminated soils, may be processed such that the solid byproduct after treatment may be reusable. Additionally, by containing and processing the gaseous byproducts containing volatilized PFAS via an emission control system, volatilized PFAS may be either absorbed or destroyed.

[0021] FIGS. 1 and 2 depict a first embodiment 100 and a second embodiment 200 of a thermomechanochemical (TMC) waste treatment system 101 for processing waste material. The first embodiment 100 includes a first set of components of the waste pre-processing subsystem 103, a TMC chamber 108, and a first set of components of a waste disposal subsystem 110. The second embodiment 200 includes a second set of components of the waste pre-processing subsystem 103, the TMC chamber 108, and a second set of components of a waste disposal subsystem 110 including an emission control system 201, a heating system 208. Both of the first embodiment 100 and the second embodiment 200 also include a controller 123. The first and the second embodiments are shown as example embodiments of the TMC waste treatment system 101 having a plurality of common components. Alternate embodiments of the TMC waste treatment system 101 may be constructed to include one or more components introduced in the first and the second embodiments.

[0022] Referring now to FIG. 1, the first embodiment 100 of the TMC waste treatment system 101 for waste processing includes the waste pre-processing subsystem 103. The waste pre-processing subsystem 103 (including the first set of components) may be configured to process a plurality of waste feedstocks coming from a plurality of containers, in preparation for TMC treatment within the TMC chamber 108. The waste pre-processing subsystem 103 may include a first feedstock 104 of waste in the liquid-solid state, the first feedstock 104 delivered to the TMC chamber 108 via a liquid-solid separation unit 106, as indicated by arrow 126. Within the liquid-solid separation unit 106, the first feedstock 104 of liquid-solid waste, e.g. Aqueous Film Forming Foam (AFFF) used for fighting high-hazard flammable liquid fires, may be partitioned into a liquid waste component, and a semi-liquid, slurry, or wet solid (SSS) waste component. The liquid component of the waste treated in the liquid-solid separation unit 106 may be transferred to a liquid containment unit 102, as indicated by arrow 128, and the SSS waste component may be transferred to the TMC chamber 108, as indicated by arrow 132. The liquid partitioned in the liquid containment unit 102 may be separately processed such as by dewatering, sedimentation, composting, incineration, solidification, etc.

[0023] Waste pre-processing subsystem 103 may also include a second feedstock 122 of semi-wet or slurry solid (SSS) waste, the second feedstock 122 delivered to the TMC chamber 108 via a dryer 120. For example, second feedstock 122 may include sludge generated from sewage processing, and/or biosolids, etc. The second feedstock 122 may be optionally fed into dryer 120, as indicated by arrow 138, to dry the SSS waste to below a threshold level of moisture contained therein, as determined by a humidity sensor 150 of the dryer 120. The threshold moisture level may be pre-calibrated threshold based on the kind of waste material

present in the second feedstock. Waste from the second feedstock 122 that has been dried in the dryer 120 may then be fed into the TMC chamber 108, as indicated by arrow 134.

[0024] Further included in the waste pre-processing subsystem 103 is a third feedstock 124 of dry solid waste, which includes waste determined to be sufficiently dry, e.g. containing a level of liquid content below the threshold moisture level. The third feedstock 124 may be sent directly into the TMC chamber 108, as indicated by arrow 140.

[0025] In conjunction with the aforementioned subsystems of the waste pre-processing subsystem 103, a dry or wet PFAS solid waste feedstock 222 may be included in the TMC preprocessing subsystem, as shown by arrow 240 in FIG. 2. The dry or wet PFAS solid waste feedstock 222 may include for example spent Granulated Activated Carbon (GAC) filters used during a previous TMC processing cycle.

[0026] In conjunction with the waste pre-processing subsystem 103, a processing reagent subsystem 118 may be included within the TMC waste treatment system 101 coupled to the TMC chamber 108, as indicated by arrow 130. The processing reagent subsystem 118 may add specialized co-milling materials (e.g. reagents) to the waste feedstocks 104, 122, 124, and 222 fed into the TMC chamber 108, based on properties of the waste feedstocks determined via information received about the waste feedstocks via a plurality of sensors contained within the waste pre-processing subsystem 103. For example, humidity sensors, mass sensors, and PFAS sensors (not shown) may be included within the waste pre-processing subsystem 103 to determine the mass, moisture content, and PFAS concentrations included within the pre-processed waste feedstocks. In response to mass, moisture content, and PFAS concentration data, the processing reagent subsystem 118 may add one or more of a type of specialized reagent (e.g. calcium hydroxide ($\text{Ca}(\text{OH})_2$)) at a given feed rate to the waste feedstocks 104, 122, 124, and 222. Sensors (not shown) for monitoring processing reagent, such as mass sensors and chemical sensors, to determine correct amount of processing reagents may be included within processing reagent sub system 118.

[0027] TMC waste treatment system 101 may also include the TMC chamber 108. TMC chamber 108 may be a chamber designed to be rotated about a central axis 105 during processing of one or more of the waste feedstocks 104, 122, 124, and 222, in order to provide mixing of one or more of the waste feedstocks 104, 122, 124, and 222 contained therein. In one example, the TMC chamber 108 may be a cylindrically-shaped vessel made out of made of steel, with dimensions of 3 ft. in diameter by 7 ft. in length; however other chamber shapes, sizes, and materials may be used. For example, TMC chamber 108 may include a milling system which may weigh in a range of 70,000-80,000 pounds. The milling system may be operable in a temperature range, for example of 200-650° F. with a nominal heat capacity of 0.111 Btu/lb-° F. (based on stainless steel), a potential rate of heat loss of 15%/hour, and an example efficiency of 80% of PFAS destruction when operational. Included within the milling system of the TMC chamber 108 are deaggregators, including mobile objects such as milling balls, or stationary impact devices such as blocks and blades attached to the inner wall of the TMC chamber 108. The TMC chamber may include one or more types of the deaggregators mentioned above. The deaggregators break up the waste material within the TMC chamber upon the

waste material coming in contact with the deaggregators. Mixing of the pre-processed waste with deaggregators and co-milling materials added from the processing reagent subsystem **118** may deagglomerate the waste material contained within the TMC chamber **108** to increase surface area exposure of the waste materials and the co-milling materials, thereby inducing thermal evolution (cleaning) of pollutants, and/or mechano-chemical destruction of pollutants. As an example, the addition of the co-milling materials in conjunction with milling may act to generate radicals from co-milling materials and localized high temperatures that may mineralize PFAS.

[0028] Referring now to FIG. 2, in addition to the inclusion of co-milling materials to the TMC chamber **108** via processing reagent subsystem **118** during TMC treatment, the TMC chamber may also be coupled to a heating system **208**. The TMC chamber **108** may be rotated around the central axis **105** during heating via the heating system **208**. A heating cycle of the TMC chamber **108**, via heating system **208**, may be activated in response to data obtained via a plurality of sensors indicating the mass, composition, moisture content, and pressure contained within the TMC chamber **108**. For example, the temperature of the heating system **208** may be set at an initial operating temperature of 400° F., but may be adaptively updated based on the mass, moisture content, temperature, and pressure of the materials contained within the TMC chamber **108**, combined with information from material sensors **146** and **148** included at the input and at the output of the chamber, monitoring waste material entering the chamber and the liberated vapor.

[0029] Sensors are included at the TMC chamber **108**, which may send data to controller **123**, which may then actuate the TMC chamber **108**, the milling system included in the TMC chamber, and the heating system **208** in response to such data; such communication is depicted by dashed lines **154** and **262**, respectively. In particular, the TMC chamber **108** may include a pressure sensor **142**, a temperature sensor **144**, and a humidity sensor **147**. The pressure sensor **142**, temperature sensor **144**, and the humidity sensor **147** may send signals to a controller **123** of pressure inside the TMC chamber **108**, temperature inside the TMC chamber, and humidity of the waste material, respectively. In response to the signals received by the controller from each of the sensors **142**, **144**, **147**, the controller **123** may adjust process parameters of the TMC process. For example, if the pressure in the TMC chamber **108** is above a threshold level, the controller **123** may adjust the pressure of a negative pressure module in order to remove gaseous byproducts of TMC processing from the chamber more quickly, and may additionally lower the temperature of heating system **208** in order to reduce the rate of volatilization of gases off of waste within the chamber.

[0030] The TMC chamber **108** may include a plurality of material sensors such as a first material sensor **146** coupled at an inlet of the TMC chamber **108** and a second material sensor **148** coupled at an outlet of the TMC chamber **108**. In addition, other material sensors may be coupled to different regions between the inlet and the outlet of the TMC chamber **108**. The material sensors may include a liquid sensor configured to determine a proportion of liquid in the waste material entering and leaving the TMC chamber. The material sensors may include a gas sensor configured to determine kind and concentration of gases (such as PFOA) entering and leaving the TMC chamber **108**. The material

sensors may also include solid sensors such as configured to determine fluoride levels in the material stream. The material sensors may comprise of one or more of conductivity sensors, acoustic sensors, and spectrometers such as Fourier transform infrared (FTIR) spectroscope to determine the properties of gases and liquids flowing in and out of the TMC chamber **108**.

[0031] During operation of the TMC chamber, process parameters including real-time measurement of speciated concentrations of liberated gases containing PFAS and other compounds may be monitored via the materials sensors **146**, **148** to ascertain input contamination levels and pollution removal/destruction efficacy, for automated system process optimization. The first material sensor **146** may determine that the input pollutant load in the waste material stream entering the TMC chamber **108**, and the second material sensor **148** may determine that the input pollutant load at the end of treatment within the TMC chamber **108**. Based on the change in pollutant load upon processing at the TMC chamber **108** the process conditions (e.g. residence time in TMC chamber and temperature) may be adjusted in real time to ensure treatment efficacy. The real-time measurement of speciated concentrations of liberated gases containing PFAS and other compounds ascertain input contamination levels and pollution removal/destruction efficacy, for automated system process optimization. The first material sensor **146** may determine characteristics such as the size distribution of the waste material, a chemical composition of the waste material, and an amount of moisture in the waste material entering the TMC chamber, and based on the characteristics of the waste material, an initial set of process parameters of the TMC chamber (such as temperature of TMC chamber, dwell time in chamber, speed of rotation of chamber, and amount of reagents added during milling) may be determined.

[0032] The initial determination and adjustments to process conditions may be based on a look-up table including optimal processing conditions corresponding to different threshold loads of pollutants entering and leaving the TMC chamber **108**. Further, the adjustments to process conditions may be based on a learning algorithm and/or a feedback mechanism.

[0033] In one example, data obtained via the materials sensors **146**, **148** may suggest that gases liberated during TMC treatment, which contain PFAS, may include an amount of PFAS above a threshold level, and in response, the process parameters including a temperature of operation of the TMC chamber and the duration of milling of the waste materials may be increased for further breakdown of the PFAS.

[0034] In another example, data obtained via the materials sensors **146**, **148** may suggest that the initially contaminated biosolid material was reduced in pollutant level to below an acceptable threshold, and the biosolid material output from the TMC chamber **108** may be safely land-applied for beneficial reuse as per application federal, state, and or local regulation. Confirmation of suitability for land application varies per local, state, tribal, or federal regulations, but typically involves measurement of nutrient levels in the material and assurance that adverse chemicals will not leach at unacceptable levels.

[0035] TMC waste treatment system **101** may also include an emission control system **201**. The emission control system may include a vacuum system **206** including a first

negative pressure module **203**, a second negative pressure module **205**, and a third negative pressure module **207**, with each of the negative pressure modules **203**, **205**, **207** fluidly coupled to a vent line **204**. The vent line **204** may be configured to flow gaseous byproducts obtained via each of the negative pressure modules **203**, **205**, **207** to an emissions control module **202**, the emissions control module **202** configured to remove gaseous byproducts during TMC processing. The first negative pressure module **203** may provide a vacuum to flow vapors coming off of waste material from waste feedstocks **104**, **122**, **124**, **222** during pre-processing of the PFAS contaminated waste. The second negative pressure module **205** may be fluidly coupled to the interior of the TMC chamber **108**, and may provide vacuum to the interior of the TMC chamber **108** in order to flow vapors coming off of the waste being processed therein. The third negative pressure module **207** may provide a vacuum to flow vapors coming off of byproduct after treatment **136**.

[0036] Gaseous byproducts flowed from each of the negative pressure modules **203**, **205**, **207** may then flow via vent line **204** to the emissions control module **202**. The emissions control module **202** may include one or more of a granulated activated carbon (GAC) filter, a catalyst, and a thermal oxidizer (TO), or other control device. Based on the level of pollutants in the byproducts being treated at the emissions control module **202**, the material output from the emissions control module may be fed back to the TMC chamber **108** for one or more processing cycles, until the level of pollutants reduce to below a threshold level of contamination, such that a byproduct after treatment **136** output from the TMC chamber may be disposed of or reused. At the emissions control module **202**, the PFAS and other toxins from the gaseous byproducts are filtered out or destroyed. For example, high volumes of gaseous byproducts that are volatile and combustible may be routed to the TO where they may be combusted, with the byproduct of the combustion released to atmosphere (as indicated by arrow **212**) or recycled back to the emissions control module **202**.

[0037] Following TMC processing of the waste material in the TMC chamber **108**, the byproduct after treatment **136** may be sorted, stored and/or disposed of via waste disposal subsystem **110**, as depicted in FIGS. **1**, **2**. Waste disposal subsystem **110** may be configured to receive solid and semi-solid byproducts after treatment of the waste material at the TMC chamber **108** and recycle at least a portion of the solid and semi-solid byproducts. Waste disposal subsystem **110** may include a plurality of disposal units, with each unit of the plurality of disposal units configured to store byproduct after treatment based on the properties of the byproduct after treatment. For example, byproduct after treatment that is determined to be non-reusable may be stored in a first unit for disposal, while byproduct after treatment that is determined to be reusable (e.g. processed biosolid waste with a below threshold level of PFAS) may be stored in a second unit for later reuse. As an example, the reusable output may be recycled back to soil from the second unit.

[0038] TMC waste treatment system **101** may also include controller **123**, as depicted in FIGS. **1**, **2**. Controller **123** may be powered through onboard stored energy via a battery (not shown). Controller **123** may be configured as a conventional microcomputer including a microprocessor unit, input/output ports, read-only memory, random access memory, keep alive memory, a controller area network (CAN) bus, etc. The controller **123** may include a controller configured to receive

input data from the various sensors, process the input data, and trigger the actuators in response to the processed input data based on instruction or code programmed therein corresponding to one or more routines. For example, data of the moisture content of each of the waste feedstocks **104**, **122**, **124**, and **222**, may be communicated to the controller via respective humidity sensors (not shown), with the communication between the waste feedstocks **104**, **122**, **124**, **222** and the controller **123** depicted here by dashed lines **152**, **162**, **164**, and **264**, respectively, in order to determine further pre-processing via the waste pre-processing subsystem **103**. Controller **123** may also communicate with the liquid-solid separation unit **106** (as indicated by dashed line **160**) via a humidity sensor (not shown). The humidity sensor of the liquid-solid separation unit **106** may be used in order to determine if the moisture level of the separated solid waste of the liquid-solid separation unit is below a threshold level in order to send first feedstock **104** into the TMC chamber **108**. Additionally, the humidity sensor **150** may be included on dryer **120**. Data received from the humidity sensor **150** may be utilized by controller **123** to adaptively set the duration and heating level to be set for dryer **120**, the communication between the controller **123** and the dryer **120** indicated by dashed line **168**.

[0039] The processing reagent subsystem **118** may also send sensor data to controller **123** and may be actuated via controller **123** to feed co-milling material into the TMC chamber **108**, as indicated by dashed line **166**. The processing reagent subsystem **118** may include a mass sensor and a belt feed sensor, in order to supply an appropriate amount of co-milling material to TMC chamber **108** in response to signals received by the controller **123**. For example, the feed rate of the co-milling material may depend on the mass of the waste contained within the TMC chamber **108**, which may decrease as TMC processing continues, as gaseous byproducts are emitted into the emission control system **201**.

[0040] The emission control system **201** may contain one or more sensors determining the chemical composition of gaseous byproducts flowed into the vent line **204** via the negative pressure modules **203**, **205**, **207**, the one or more sensors (not shown) sending data of the chemical composition (real-time monitoring) of the gaseous byproducts to the controller **123**, which may then actuate the pressure modules to generate more or less vacuum depending on said data. The communication between the emission control system **201** and the controller is depicted by dashed line **214**. For example, the sensors may include a PFAS sensor to determine a concentration of PFAS within the gaseous byproducts flowed into the emission control system **201**. Sensors may also include a mass air flow (MAF) sensor, such that the controller **123** may adjust TMC process parameters, (e.g., feed rate of processing reagent, temperature of heating system **208**, rotation rate of TMC chamber **108**) based on the amount gaseous byproducts generated. Sensors may also be included for other contaminants, and the controller **123** may adjust TMC processing parameters based on data received by controller **123** of the amount of contamination of the gaseous byproducts. An example of an added contaminant sensor is an online-Fourier transform infrared spectroscopy unit. Another example of an added contaminant sensor is a laser-ablation fluorine detector.

[0041] FIGS. **3A**, **3B** illustrate a method **300** for operating a thermomechanochemical (TMC) system (such as TMC waste treatment system **101** of FIGS. **1**, **2**) for processing

PFAS-contaminated waste. Method **300** and all other methods described herein will be described in reference to the systems described herein and with regard to FIGS. **1**, **2** but it should be understood that similar methods may be applied to other systems without departing from the scope of this disclosure. Method **300** may be carried out by controller **123**, and may be stored in non-transitory memory. Instructions for carrying out method **300** may be executed by the controller in conjunction with signals received from the TMC via a plurality of sensors included therein.

[0042] At **302**, method **300** includes determining details of waste properties to be processed by the TMC system. Broad waste categories will be known to operators based on waste manifest from generators. The broad categories of waste may be one of a liquid-solid waste, dry solid waste, or semi-wet or slurry solid waste. As an example, the type of incoming waste may be determined based on moisture content of the waste, initially estimated by waste producer and confirmed via a humidity sensor. For example, liquid-solid waste may have a moisture content of >30%, semi-wet or slurry solid waste may have a moisture content of 10%-30%, and dry waste may have a moisture content of <1%-<10%.

[0043] At **304**, method **300** may include determining if the incoming waste is dry solid waste. If the waste is not determined to be dry solid waste, method **300** may proceed to **306**.

[0044] At **306**, method **300** may include determining if the incoming waste is semi-wet or slurry solid (SSS) waste. If the waste is not determined to be SSS waste, the waste may then be inferred to be liquid-solid waste feedstock (such as first feedstock **104** of FIG. **1**), and method **300** may proceed to **308** to separate liquid waste from solid waste in the liquid-solid waste. The liquid solid waste may be transferred (as indicated by arrow **126** of FIG. **1**) to a liquid-solid separation unit (such as liquid-solid separation unit **106** of FIG. **1**). As an example, solid waste may be partitioned from liquid waste within the liquid-solid separation unit via one or more of clarification (e.g., gravity sedimentation), centrifugal separation, delayed cake filtration, belt filters, vacuum dryers, etc. Following separation of the liquid waste from the solid waste within the liquid-solid separation unit, at **310**, the partitioned liquid waste within the liquid-solid separation unit may be transferred (as indicated by arrow **128** of FIG. **1**) to a liquid containment unit (such as liquid containment unit **102** of FIG. **1**) for later processing. The remaining waste may then be SSS waste, to be added to a TMC chamber (such as TMC chamber **108** of FIG. **1**), as indicated by arrow **132** of FIG. **1**. At **314**, the SSS waste may be combined with appropriate processing reagents via a processing reagent subsystem (such as processing reagent subsystem **118** of FIGS. **1**, **2**) in the TMC chamber. For example, the processing reagents may include silica (SiO_2), potassium hydroxide (KOH), calcium oxide (CaO), and/or calcium hydroxide (Ca(OH)_2). The processing reagents, and the feed rate may be determined based on the mass of the waste feedstock, and the chemical properties of the waste feedstock, as determined by a material properties sensor (such as first material sensor **146** of FIGS. **1**, **2**). Following **314**, method **300** may then proceed to **318**.

[0045] At **306**, if it is determined that the incoming waste is SSS waste, then method **300** may proceed to **312** to pre-dry the SSS waste via a dryer (such as dryer **120** of FIG. **1**). The dryer may operate at a temperature of **600** for

example. Drying of the SSS waste via the dryer may dry the SSS waste until it is below a threshold level of moisture, as determined by a humidity sensor (such as humidity sensor **150** of FIG. **1**). The threshold level of moisture may be a level of moisture below which the SSS waste may be considered to be dry solid waste. For example, the threshold level of moisture for the SSS waste to be inputted into the TMC chamber may be 10-20%. Following drying of the SSS waste via the dryer, method **300** may then proceed to **314** to combine semi-wet or slurry solid waste with appropriate processing reagents in the TMC chamber. The appropriate processing reagents, and the feed rate may be determined based on the mass of the waste feedstock, and the chemical properties of the waste feedstock, as determined by the first material properties sensor. Following **314**, method **300** may then proceed to **318**.

[0046] Returning to **304**, if it is determined that the incoming waste is dry solid waste (such as third feedstock **124** of FIG. **1**), method **300** may then proceed to **316** to combine the dry solid waste with appropriate processing reagents in the TMC chamber. The appropriate processing reagents, and the feed rate may be determined based on the mass of the waste feedstock, and the chemical properties of the waste feedstock, as determined by the first material properties sensor. Following **316**, method **300** may then proceed to **318**.

[0047] At **318**, method **300** may include setting the process parameters of TMC treatment of waste material transferred to the TMC chamber. The process parameters may depend on the type of waste feedstock (e.g. dry solid waste, as from **316** or SSS waste, as from **314**). The process parameters of the TMC processing include, at **320**, setting the operating temperature of a heater (such as heating system **208** of FIG. **2**). The operating temperature of the heater may depend on the type of waste material and the processing reagents added. For example, for SSS waste, the operating temperature may be in a range of 160° F. to 400° F., while for dry solid waste, the operating temperature may be in a range of 160° F. to 650° F. During heating, the operating temperature may be adaptively adjusted based on temperature, pressure, and volume of gaseous byproduct generated in response to TMC treatment of waste, as determined by temperature, pressure, and materials sensors, respectively (such as temperature sensor **144**, pressure sensor **142**, and materials sensors **146**, **148** of FIGS. **1**, **2**). Adaptation of the operating temperature may, in one example, be utilized in order to maintain energy efficiency of the TMC process. In another example, adaptation of the operating temperature may be utilized in order to reduce pressure within the TMC chamber during operation to below a threshold level of pressure. In yet another example, adaptation of the operating temperature may be utilized in order to make sure that the temperature of the waste material being processed in the TMC chamber is below a threshold temperature, beyond which recyclability of the output waste byproduct is possible.

[0048] The process parameters of the TMC processing include, at **322**, setting the heating duration. The heating duration of the heater may depend on the type of waste material and the processing reagents added. For example, for SSS waste, the operating heating duration may be in a range of 6 hours, while for dry solid waste, the heating duration may be in a range of 3 hours. During heating, a projected heating duration may be adaptively adjusted based on tem-

perature, pressure, and volume of gaseous byproduct generated in response to TMC treatment of waste, as determined by temperature, pressure, and materials sensors. For example, adaptation of the heating duration may be utilized in order to maintain energy efficiency of the TMC process.

[0049] The process parameters of the TMC processing include, at **324**, setting the milling duration (such as using ball milling or any other form of deaggregator) and speed of rotation of the TMC chamber. The milling duration may depend on the type of waste material and the processing reagents added. For example, for SSS waste, the operating milling duration may be in a range of 5 minutes to 2 hours, while for dry solid waste, the milling duration may be in a range of 20 minutes to 2 hours. The speed of rotation of the TMC chamber may similarly depend on the type of waste material and the processing reagents added. For example, for SSS waste, the operating rotation speed of the TMC chamber may be in a range of 10 revolutions per minute, while for dry solid waste, the operating rotation speed of the TMC chamber may be in a range of 30 revolutions per minute. During the milling process, a projected milling duration may be adaptively adjusted based on temperature, pressure, and volume of gaseous byproduct generated in response to TMC treatment of waste, as determined by temperature, pressure, and materials sensors, respectively. Similarly, the rotation speed of the TMC chamber may be adapted based on similar data, for example in order to maintain energy efficiency of the TMC processing.

[0050] At **326**, method **300** may include determining if conditions are met for removal of gaseous byproducts from the TMC chamber. For example, if the pressure within the TMC chamber is above a threshold level, then a second negative pressure module (such as second negative pressure module **205** of FIG. 2) of an emission control system (such as emission control system **201** of FIG. 2) may be switched on in order to flow gaseous byproducts of the TMC treatment out of the chamber. If conditions are not met for removal of gaseous byproducts, method **300** may proceed to **328** to continue processing, and then may return to **336**. Otherwise, method **300** may proceed to **330**.

[0051] At **330**, method **300** includes applying a negative pressure to flow gaseous byproducts to emission control system. Applying negative pressure includes switching on each of a negative pressure control module (such as negative pressure modules **203**, **205**, **207** of FIG. 2) in order to remove gaseous byproducts during TMC treatment of waste in the TMC chamber. The gaseous byproducts routed to each of the first negative pressure module, the second negative pressure module, and the third negative pressure module may then enter a vent line (such as vent line **204** of FIG. 2), after which it may be sent to an emissions control module (such as emissions control module **202** of FIG. 2). As described in relation to FIG. 2, the negative pressure modules may intake gaseous byproducts during each stage of the waste treatment (waste material, waste undergoing TMC treatment, and byproduct after treatment). In particular, the first negative pressure module may provide a vacuum to flow vapors coming off of waste material from waste feedstocks (such as waste feedstocks **104**, **122**, **124**, **222** of FIGS. 1, 2) during pre-processing of the PFAS-contaminated waste. The second negative pressure module may be fluidly coupled to the interior of the TMC chamber, and may provide vacuum to the interior of the TMC chamber in order to flow vapors coming off of the waste being processed

therein. The third negative pressure module may provide a vacuum to flow vapors coming off of a byproduct after treatment (such as byproduct after treatment **136** of FIGS. 1, 2) after TMC processing.

[0052] At **332**, method **300** may include utilizing pollution control technologies, such as granulated activated carbon (GAC), a catalyst, or thermal oxidizer (TO), via an emissions control module (such as emissions control module **202** of FIG. 2) based on the pressure, volume, and temperature of gaseous byproducts produced during the treatment process. For example, if the volume of flammable gaseous byproducts produced per unit time (as determined by the MAF sensor) during the treatment process are above a threshold flow rate, then the high volumes of gaseous byproducts may be treated via thermal oxidation, whereby the gaseous byproducts may be combusted.

[0053] The choice of using a specific pollution control technology may also depend on the temperature of the gaseous byproducts. For example, if the temperature of the gaseous byproducts is above a threshold temperature, the GAC may not be used and a catalyst may be more appropriate. The choice of using GAC, a catalyst, or TO may also depend on the level of contamination in the gaseous byproducts, in addition to the level of contamination of the GAC and catalysts. For example, if the GAC is already loaded above a first threshold level (as determined by e.g. a pressure sensor attached to the GAC), and the catalyst is loaded above a second threshold level (as determined by e.g. a pressure sensor attached to the catalyst), then use of the TO may be more appropriate, in order to treat the gaseous byproducts. Similarly, if the amount of contaminants in the gaseous byproducts is above a threshold level of contamination as determined by a PFAS sensor and other contaminant sensors of the emission control system, the TO may be used. Otherwise, if the levels of loading of the GAC and/or catalyst are below their respective threshold levels, the temperature of the gaseous byproducts is within the acceptable temperature range for usage for either of the GAC and/or catalyst, and the level of contamination of the gaseous byproducts is below a threshold level, either of the GAC or the catalyst may be used to filter the gaseous byproduct.

[0054] At **334**, method **300** may include determining the quality/type of non-gaseous byproduct generated from the TMC processing (e.g. the byproduct after treatment). The quality/type of byproduct after treatment may be determined by a second material sensor (such as second material sensor **148** of FIGS. 1, 2) coupled to an output of the TMC chamber. For example, the output sensor may determine the amount of contaminants retained within the byproduct after treatment, such as a percentage of PFAS contaminant in the byproduct after treatment, among other contaminants.

[0055] At **336**, method **300** may include determining if a portion of the non-gaseous byproduct (e.g. the byproduct after treatment) is recyclable. Determining if a portion of the byproduct after treatment may include utilizing the measure of contaminants from **324** to determine if a portion of the byproduct after treatment is below a threshold level of contamination. If it is determined that the byproduct after treatment is not recyclable, then method **300** may proceed to **338**, which includes disposing of the non-recyclable non-gaseous byproduct via a disposal subsystem (such as waste disposal subsystem **110** of FIGS. 1, 2). Following **338**, method **300** may then optionally proceed to **342**. However,

if it is determined that a portion of the waste material is recyclable, then method **300** may proceed to **340** to store the recyclable portion of the non-gaseous byproduct for later reuse, and may dispose of the rest of the non-gaseous byproduct via the disposal subsystem. In one example, the recyclable portion may be released such as added back to soil. Following **340**, method **300** may then optionally proceed to **342**.

[0056] At **342**, method **300** may include processing the used GAC filter as dry solid waste for reuse via the TMC system. Processing the GAC filter may proceed if the level of loading of the GAC filter is above the first threshold level of loading as determined in **332**. If the level of loading of the GAC filter is above the first threshold level of loading, the GAC may be circulated via a GAC return line (such as GAC return line **210** of FIG. **2**) as dry solid waste to be added to the TMC chamber. TMC processing of the GAC filter may then follow from **316** of method **300**.

[0057] At **344**, method **300** includes determining if conditions are met for completing the TMC waste processing. Conditions for completing TMC waste processing may include the contents of the gaseous byproducts being below a level of contamination as determined by one or more contamination sensors of the emission control system, a flow rate of gaseous byproducts being below a threshold flow rate of the emission control system, a feed rate of the waste feedstocks being 0, the rate of mass of waste material outputted by the TMC chamber being below a threshold level, and the level of contamination of the byproduct after treatment being below a threshold level as determined by the second material sensor of the TMC chamber. If the conditions for completing TMC waste processing are not met, method **300** may proceed to **346** to continue TMC waste processing. If the conditions for completing TMC waste processing are met, then method **300** may proceed to **348** to suspend rotation of the TMC chamber, heating of the chamber via the heater, negative pressure application via the negative pressure modules of the emission control system, and the feeding of processing reagents (co-milling materials) to the chamber. Following **348**, method **300** may end.

[0058] In this way, a thermomechanochemical (TMC) waste system may be operated for processing PFAS-contaminated waste. Waste material may be fed to the TMC chamber from one or more containers housing waste material being in a liquid-solid state, a semi-wet or slurry solid (SSS) state, and/or a dry solid state. The waste material may be processed at the TMC chamber by milling at elevated temperatures in a presence of co-milling reagents, and byproducts obtained after processing of the waste material at the TMC chamber may be removed via the disposal system and/or the emissions control module. The co-milling reagents may be added to the TMC chamber from the processing reagent subsystem, the co-milling reagents chemically reacting with the waste material during milling of the waste material via deaggregators included within the TMC chamber.

[0059] By combining thermal processing with mechanochemical processing as part of treating PFAS-contaminated waste feedstocks, multiple types of waste feedstocks may be treated by a single thermomechanochemical (TMC) system. By utilizing mechanochemical treatment in conjunction with thermal treatment of PFAS contaminated waste, lower temperatures may be used during TMC treatment as compared with a solely thermal treatment, allowing a greater

portion of the byproduct after treatment to be recyclable. Additionally, by utilizing one or more of a catalyst, granulated activated carbon (GAC) filter, and a thermal oxidizer (TO) as part of an emission control system, gaseous byproducts of TMC treatment, with volatilized PFAS and other contaminants, may be treated, reducing emissions of harmful contaminants into the atmosphere during treatment of PFAS contaminated waste. By adaptively controlling TMC process parameters (such as feed rate of co-milling materials, temperature and pressure of the TMC chamber, and amount of negative pressure applied via the negative pressure modules of the emission control system), TMC treatment may be optimized for energy efficiency, in addition to optimal reduction of PFAS and other contaminants in the waste feedstock. By allowing treatment of a spent GAC filter via the TMC system, reuse and/or proper disposal of a GAC filter may be achieved.

[0060] The disclosure provides support for a system for treatment of waste material, comprising: a thermomechanochemical (TMC) chamber including a milling system, a heating system coupled to the TMC chamber, the heating system configured to co-operate with the milling system to process the waste material, and plurality of containers coupled to the TMC chamber at a first end, the plurality of containers including the waste material in one or more of a liquid-solid state, a semi-wet or slurry solid state, and a dry solid state. In a first example of the system, the waste material includes per- and polyfluoroalkyl substances (PFAS) comprising perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). In a second example of the system, optionally including the first example, the plurality of containers include one or more of a first feedstock of waste material in the liquid-solid state, a second feedstock of waste material in the semi-wet or slurry solid state, and a third feedstock of waste material in the dry solid state, the first feedstock delivered to the TMC chamber via a solid-liquid separator, the second feedstock delivered to the TMC chamber via a dryer, and the third feedstock delivered directly to the TMC chamber. In a third example of the system, optionally including one or both of the first and second examples, the system further comprises: a plurality of sensors including one or more of a temperature sensor, a pressure sensor, and material sensors coupled to the TMC chamber, and a humidity sensor coupled to the dryer, wherein the material sensors are coupled to an inlet and an outlet of the TMC chamber, the material sensors including one or more of a gas sensor, a liquid sensor, and a solid sensor. In a fourth example of the system, optionally including one or more or each of the first through third examples, the milling system in the TMC chamber is coupled to a processing reagent subsystem supplying co-milling reagents to the milling system, the milling system including deaggregators, the deaggregators including one or more of milling balls, blocks, and blades. In a fifth example of the system, optionally including one or more or each of the first through fourth examples, the reagents are one or more of silica (SiO₂), potassium hydroxide (KOH), calcium oxide (CaO), and calcium hydroxide (Ca(OH)₂). In a sixth example of the system, optionally including one or more or each of the first through fifth examples, the TMC chamber is rotatable about its central axis during processing of the waste material. In a seventh example of the system, optionally including one or more or each of the first through sixth examples, the TMC chamber is coupled to an emissions control module via one

or more negative pressure modules, the emissions control module including one or more of a granulated activated carbon (GAC) filter, a catalyst, and a thermal oxidizer (TO) configured to treat gaseous byproducts recovered from the TMC chamber. In an eighth example of the system, optionally including one or more or each of the first through seventh examples, the TMC chamber is coupled to a disposal system configured to receive solid and semi solid byproducts obtained after treatment of the waste material at the TMC chamber and recycle at least a portion of the solid and semi solid byproducts. In a ninth example of the system, optionally including one or more or each of the first through eighth examples, the one or more negative pressure modules include a first negative pressure module coupled to the plurality of containers including the waste material and configured to remove gaseous components of the waste material entering the TMC chamber, a second negative pressure module coupled to the TMC chamber and configured to remove the gaseous byproducts from the TMC chamber during processing of the waste material, and a third negative pressure module coupled to the disposal system and configured to remove the gaseous byproducts from the disposal system.

[0061] The disclosure also provides support for a method for a thermomechanicochemical (TMC) waste treatment, comprising: feeding a waste material to a TMC chamber from one or more containers housing the waste material in one or more of a liquid-solid state, a semi-wet or slurry solid state, and a dry solid state, processing the waste material at the TMC chamber by milling at elevated temperatures in a presence of co-milling reagents, and removing byproducts obtained after processing of the waste material at the TMC chamber via one or both of a disposal system and an emissions control module. In a first example of the method, the feeding of the waste material in the liquid-solid state includes, separating the liquid-solid state into a solid component and a liquid component at a separator, and then feeding the solid component to the TMC chamber, and wherein the feeding of the waste material in the semi-wet or slurry solid state includes, drying the waste material in a dryer and the feeding of waste material in the dry solid state to the TMC chamber. In a second example of the method, optionally including the first example, the co-milling reagents are added to the TMC chamber from a processing reagent subsystem, the co-milling reagents chemically reacting with the waste material during milling of the waste material via deaggregators included within the TMC chamber. In a third example of the method, optionally including one or both of the first and second examples, the deaggregators include one or more of milling balls, blades, blocks, and other impact devices, and wherein the reagents include one or more of silica (SiO_2), potassium hydroxide (KOH), calcium oxide (CaO), and calcium hydroxide ($\text{Ca}(\text{OH})_2$). In a fourth example of the method, optionally including one or more or each of the first through third examples, the method further comprises: adjusting process parameters including an amount of co-milling reagents added to the TMC chamber, a duration of milling, a temperature of the TMC chamber, and a duration of heating of the TMC chamber based on characteristics of the waste material, the characteristics including a size distribution of particles of the waste material, a chemical composition of the waste material, and an amount of moisture in the waste material. In a fifth example of the method, optionally including one or more or

each of the first through fourth examples, removing the byproducts include routing gaseous byproducts from the TMC chamber to the emissions control module by application of negative pressure via one or more negative pressure modules, the emissions control module including one or more of granulated activated carbon (GAC) filter, a catalyst, and a thermal oxidizer (TO) filter, the method further comprising, based on a level of pollutants in an output product of the GAC filter, recycling the output product to the TMC chamber for one or more cycles of processing. In a sixth example of the method, optionally including one or more or each of the first through fifth examples, removing the byproducts via the disposal system includes separating a reusable portion of the byproducts for recirculation and disposing a remaining portion of the byproducts. In a seventh example of the method, optionally including one or more or each of the first through sixth examples, the method further comprises: monitoring real-time process conditions including a first level of pollutants in the waste material at an inlet of the TMC chamber and a second level of pollutants in the waste material at an outlet of the TMC chamber via material sensors coupled to the TMC chamber, and adjusting the process parameters based on the first level and the second level of pollutants. In an eighth example of the method, optionally including one or more or each of the first through seventh examples, monitoring the second level of pollutants includes real-time measurement of speciated concentrations of liberated gases containing PFAS and other compounds.

[0062] The disclosure also provides support for a thermomechanicochemical (TMC) waste treatment system, comprising: a feeding system for waste material coupled to a TMC chamber, the TMC chamber including a plurality of milling balls or mechanisms, a heating system coupled to the TMC chamber, a processing reagent subsystem coupled to the TMC chamber, the processing reagent subsystem configured to deliver co-milling reagents to the TMC chamber, a disposal system coupled to the TMC chamber, the disposal system configured to remove gaseous and non-gaseous byproducts remaining after treatment of the waste material at the TMC chamber, and a real-time monitoring system including one or more material sensors enabling automated process optimization. In a first example of the system, the system further comprises: a controller including executable instructions stored in a non-transitory memory that cause the controller to: dry the waste material at the feeding system, feed the dried waste material to the TMC chamber from the feeding system, add a milling reagent to the TMC chamber, adjust process parameters including a temperature of the TMC chamber and a duration of milling based on characteristics of the waste material including a size distribution of particles of the waste material, a chemical composition of the waste material, and an amount of humidity in the waste material, wherein the automated process optimization includes further updating the process parameters based on output of the one or more material sensors coupled to an inlet and an outlet of the TMC chamber, and rotate the TMC chamber about its central axis while milling the waste material at the adjusted temperature, route a first gaseous portion of byproducts from the TMC chamber to an emissions control system by applying negative pressure at the TMC chamber and downstream of the TMC chamber, route

a second portion of the byproducts to a recycling chamber for reuse, and route a third, remaining portion of the byproducts to a disposal system.

[0063] The following claims particularly point out certain combinations and sub-combinations regarded as novel and non-obvious. These claims may refer to “an” element or “a first” element or the equivalent thereof. Such claims should be understood to include incorporation of one or more such elements, neither requiring nor excluding two or more such elements. Other combinations and sub-combinations of the disclosed features, functions, elements, and/or properties may be claimed through amendment of the present claims or through presentation of new claims in this or a related application. Such claims, whether broader, narrower, equal, or different in scope to the original claims, also are regarded as included within the subject matter of the present disclosure.

1. A system for treatment of waste material, comprising: a thermomechanochemical (TMC) chamber including a milling system; a heating system coupled to the TMC chamber, the heating system configured to co-operate with the milling system to process the waste material; and plurality of containers coupled to the TMC chamber at a first end, the plurality of containers including the waste material in one or more of a liquid-solid state, a semi-wet or slurry solid state, and a dry solid state.
2. The system of claim 1, wherein the waste material includes per- and polyfluoroalkyl substances (PFAS) comprising perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS).
3. The system of claim 1, wherein the plurality of containers include one or more of a first feedstock of waste material in the liquid-solid state, a second feedstock of waste material in the semi-wet or slurry solid state, and a third feedstock of waste material in the dry solid state, the first feedstock delivered to the TMC chamber via a solid-liquid separator, the second feedstock delivered to the TMC chamber via a dryer, and the third feedstock delivered directly to the TMC chamber.
4. The system of claim 3, further comprising a plurality of sensors including one or more of a temperature sensor, a pressure sensor, and material sensors coupled to the TMC chamber, and a humidity sensor coupled to the dryer, wherein the material sensors are coupled to an inlet and an outlet of the TMC chamber, the material sensors including one or more of a gas sensor, a liquid sensor, and a solid sensor.
5. The system of claim 1, wherein the milling system in the TMC chamber is coupled to a processing reagent subsystem supplying co-milling reagents to the milling system, the milling system including deaggregators, the deaggregators including or more of milling balls, blocks, and blades.
6. The system of claim 5, wherein the reagents are one or more of silica (SiO_2), potassium hydroxide (KOH), calcium oxide (CaO), and calcium hydroxide ($\text{Ca}(\text{OH})_2$).
7. A system of claim 1, wherein the TMC chamber is coupled to an emissions control module via one or more negative pressure modules, the emissions control module including one or more of a granulated activated carbon (GAC) filter, a catalyst, and a thermal oxidizer (TO) configured to treat gaseous byproducts recovered from the TMC chamber.

8. The system of claim 7, wherein the TMC chamber is coupled to a disposal system configured to receive solid and semi solid byproducts obtained after treatment of the waste material at the TMC chamber and recycle at least a portion of the solid and semi solid byproducts.

9. The system of claim 8, wherein the one or more negative pressure modules include a first negative pressure module coupled to the plurality of containers including the waste material and configured to remove gaseous components of the waste material entering the TMC chamber, a second negative pressure module coupled to the TMC chamber and configured to remove the gaseous byproducts from the TMC chamber during processing of the waste material, and a third negative pressure module coupled to the disposal system and configured to remove the gaseous byproducts from the disposal system.

10. A method for a thermomechanochemical (TMC) waste treatment, comprising:

feeding a waste material to a TMC chamber from one or more containers housing the waste material in one or more of a liquid-solid state, a semi-wet or slurry solid state, and a dry solid state;

processing the waste material at the TMC chamber by milling at elevated temperatures in a presence of co-milling reagents; and

removing byproducts obtained after processing of the waste material at the TMC chamber via one or both of a disposal system and an emissions control module.

11. The method of claim 10, wherein the feeding of the waste material in the liquid-solid state includes, separating the liquid-solid state into a solid component and a liquid component at a separator, and then feeding the solid component to the TMC chamber, and wherein the feeding of the waste material in the semi-wet or slurry solid state includes, drying the waste material in a dryer and the feeding of waste material in the dry solid state to the TMC chamber.

12. The method of claim 10, wherein the co-milling reagents are added to the TMC chamber from a processing reagent subsystem, the co-milling reagents chemically reacting with the waste material during milling of the waste material via deaggregators included within the TMC chamber.

13. The method of claim 12, wherein the deaggregators include one or more of milling balls, blades, blocks, and other impact devices, and wherein the reagents include one or more of silica (SiO_2), potassium hydroxide (KOH), calcium oxide (CaO), and calcium hydroxide ($\text{Ca}(\text{OH})_2$).

14. The method of claim 13, further comprising, adjusting process parameters including an amount of co-milling reagents added to the TMC chamber, a duration of milling, a temperature of the TMC chamber, and a duration of heating of the TMC chamber based on characteristics of the waste material, the characteristics including a size distribution of particles of the waste material, a chemical composition of the waste material, and an amount of moisture in the waste material.

15. The method of claim 10, wherein removing the byproducts include routing gaseous byproducts from the TMC chamber to the emissions control module by application of negative pressure via one or more negative pressure modules, the emissions control module including one or more of granulated activated carbon (GAC) filter, a catalyst, and a thermal oxidizer (TO) filter, the method further comprising, based on a level of pollutants in an output

product of the GAC filter, recycling the output product to the TMC chamber for one or more cycles of processing.

16. The method of claim **14**, wherein removing the byproducts via the disposal system includes separating a reusable portion of the byproducts for recirculation and disposing a remaining portion of the byproducts.

17. The method of claim **14**, further comprising, monitoring real-time process conditions including a first level of pollutants in the waste material at an inlet of the TMC chamber and a second level of pollutants in the waste material at an outlet of the TMC chamber via material sensors coupled to the TMC chamber, and adjusting the process parameters based on the first level and the second level of pollutants.

18. The method of claim **17**, wherein monitoring the second level of pollutants includes real-time measurement of speciated concentrations of liberated gases containing PFAS and other compounds.

19. A thermomechanicochemical (TMC) waste treatment system, comprising:

- a feeding system for waste material coupled to a TMC chamber;
- the TMC chamber including a plurality of milling balls or mechanisms;
- a heating system coupled to the TMC chamber;
- a processing reagent subsystem coupled to the TMC chamber, the processing reagent subsystem configured to deliver co-milling reagents to the TMC chamber;
- a disposal system coupled to the TMC chamber, the disposal system configured to remove gaseous and non-gaseous byproducts remaining after treatment of the waste material at the TMC chamber; and

a real-time monitoring system including one or more material sensors enabling automated process optimization.

20. The system of claim **19**, further comprising, a controller including executable instructions stored in a non-transitory memory that cause the controller to:

- dry the waste material at the feeding system;
- feed the dried waste material to the TMC chamber from the feeding system;
- add a milling reagent to the TMC chamber;
- adjust process parameters including a temperature of the TMC chamber and a duration of milling based on characteristics of the waste material including a size distribution of particles of the waste material, a chemical composition of the waste material, and an amount of humidity in the waste material, wherein the automated process optimization includes further updating the process parameters based on output of the one or more material sensors coupled to an inlet and an outlet of the TMC chamber;
- rotate the TMC chamber about its central axis while milling the waste material;
- route a first gaseous portion of byproducts from the TMC chamber to an emissions control system by applying negative pressure at the TMC chamber and downstream of the TMC chamber;
- route a second portion of the byproducts to a recycling chamber for reuse; and
- route a third, remaining portion of the byproducts to a disposal system.

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